P E A R L P V

Reliability engineering and modelling and predictive ageing

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Why do ALT testing (and LT modelling?)

Why do ALT testing? is normally used to provide information on

1) identify optimal material sets
2) Provide relative stability of a PV module compared to another
3) Info on a products failure mechanisms
4) expected life in the field
5) Estimation on warranty provision

qualitative

quantitative

Broadly speaking, there are the two types: qualitative tests (eg HALT) and quantitative (QALT) accelerated life tests (eg for predictive ageing).

Modelling of reliability using QALT addresses lifetime and tries quantifies degradation through the application of mathematical models

Agenda

- **1. Understanding Basic Reliability modelling and theory**
  - Application of Bathtub Curve theory
  - Importance of Early Life Reliability and the Importance of Distributions in Reliability modelling
  - Definition of Hazard Rate
  - Realising the Importance of Component Reliability and MTTF
  - Combining different MTTF levels for Different Components or Sub-Assemblies or systems
- **2. Accelerated Stress Testing and effect of Activation Energy**
  - Real Life examples of how to calculate Activation Energy level from experimental work at component level
  - High temp. Arrenius model and activation energies
  - Maximising Acceleration Factors by combining Temperature, Thermal Cycling, and Humidity
- **3 Modern approaches to reliability in PVs**
  - Multistress testing of solar cells
  - Strategies in modern industries

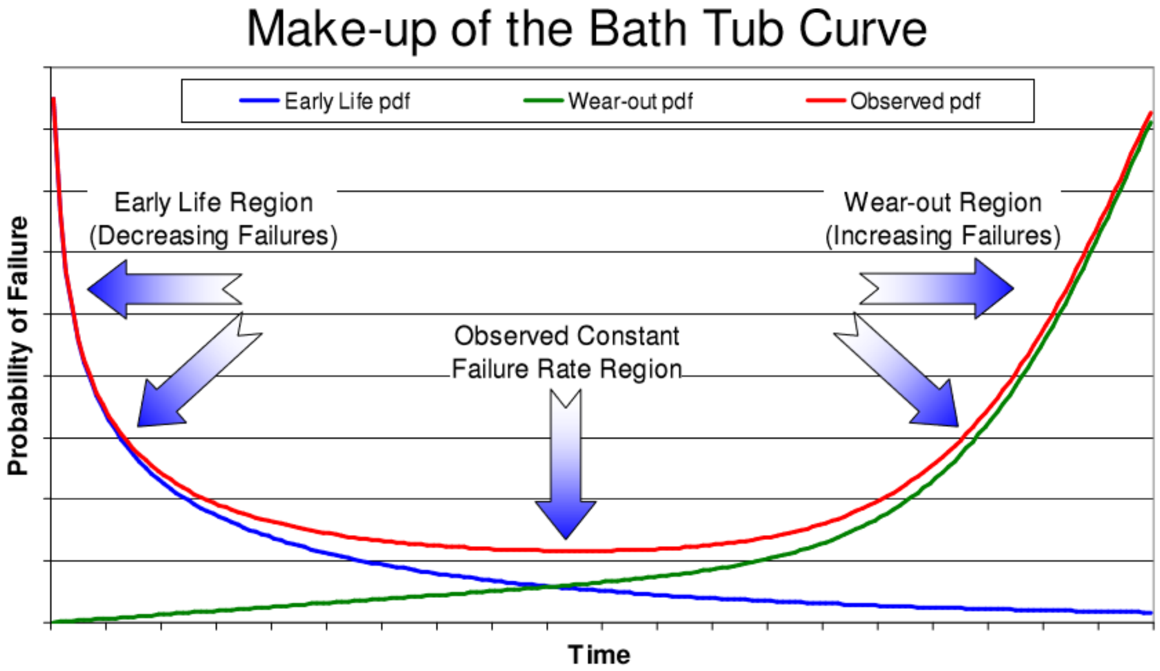
General Reliability Principles

•Reliability is the probability that a device will NOT fail to perform its intended function(s) during a specified time interval when operated under stated conditions.

R(t) = Reliability = 1 - Probability of Failure

$$R(t) = 1 - F(t) = 1- - \int_0^{\partial} f(t)$$

F(t) is the cumulative distribution function.
f(t) is the probability density function



General Reliability Principles

The pattern of failure for products / components over their useable lifetime is often referred to as the bathtub curve.

•The bathtub curve is an observed pdf with three distinct regions: -Early life -Constant or steady state life -Wear-out

•These three regions can be explained mathematically by two overlapping probability density functions.

-The pdf for the early life portion starts with a high probability of failure that declines quickly over time, but does not go to zero.

-The pdf for the wear-out region has an increasing failure probability and starts later in the lifetime of the product.

-The sum of the two pdfs results in the steady state life region that appears to have a relatively constant probability of failure (freak failures…)

General Reliability Principles

The trimodal Distribution; Often a new product will display three different failure distributions

-Infant Mortality - Manufacturing errors, defects lack of process control

-Freak Population - Manufacturing anomalies requiring longer time to fail

–Main Population – Defect free parts that continue to function into wearout

- Testing in Organic PVs has shown each to have following content with respect to total failure
    - -ELF 0.1-3%
    - -Freak population 2-10%
    - -Main Population (wearout) > 90%

- This is not dissilimar to types of failures seen e.g electronics industry

- Your objective is as a quality engineering is to remove first 2 distributions prior to shipment

Basic Reliability modelling

- The Reliability Engineer is often required to make a prediction of future product performance based on an available set of data, usually collected from representative samples.

- Probability and statistics are used widely. Probability helps to quantify the likelihood of an uncertain event. Statistics pertains to the collection, analysis, interpretation and presentation of data.

A Probability Distribution is a means of mathematically describing the probability of failure over time.

-In Reliability Engineering, a product “lifetime distribution” is most often described by the associated probability density function (pdf), the cumulative distribution function (cdf), or both.

- The pdf is a mathematical equation used to describe the probability that a random variable takes on a specific value.

- Mathematically, the pdf is the probability that a random variable, x, can be found in the very small interval between x and $x+dx$.

$$\text{pdf} = f(x)dx = P(x \leq x' \leq x + dx)$$

- The pdf can be thought of as a smoothed version of a histogram

Basic Reliability Mathematics

• If F(X) is the probability that the time to failure for a component is 500 hours or less, then 1 -F(x) is the probability of surviving beyond 500 hours.

This is known as the *Reliability function, - (exponential model)*

$$R(t) = 1 - F(t) = e^{-\lambda t}$$

-For example, if the probability of a component failing within 500 hours is 0.05 (5%) then the reliability of the component at 500 hours is 0.95 (95%).

•The instantaneous failure rate, also known as the <u>Hazard rate (λ)</u>, can be determined by dividing the number of units failing during a time period by the number of units surviving at the beginning of that time period. As the period of time is decreased to the limit of zero, this simplifies to:

$$\lambda(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)}$$

•HAZARD rate (λ) sometimes used or MTTF = 1/ λ

Probability Distributions

•The Exponential distribution is used to model a constant probability of failure.

•With the exponential distribution, unfailed units are 'good as new' because failure behavior is not dependent on past history.

•The exponential distribution has traditionally been used to model the constant failure period of the bath tub curve.

-This simplifies calculations but (warning!) does not describe semiconductor products very well!

•The exponential is typically used as a single parameter distribution with the failure rate, λ, as the scale parameter.

EXPONENTIAL EXAMPLE 1

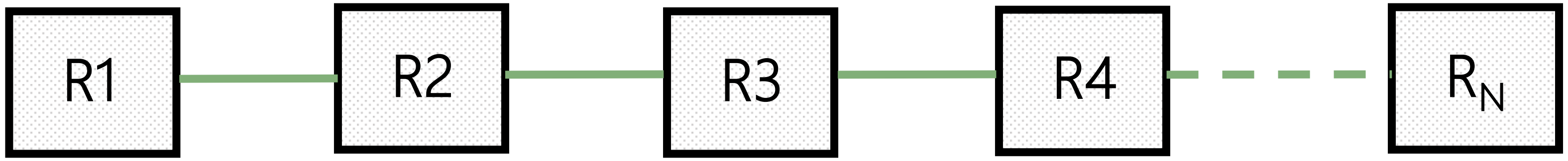
What is the required MTTF of a bypass diode if reliability of 0.999 is to be achieved during 3000 operational hours

Answer

$R(t) = e^{-\lambda t}$ $0.999 = e^{-\lambda(3000)}$ $\ln(0.999) = -(3000)\lambda$ λ= 3.34 x 10 e -7 per hour

MTTF = 1 / λ= 2,994,011 hrs

RELIABILITY OF SERIES SYSTEMS



- System will fail if any one of the units fails i.e System is no more reliable than its weakest component
- For a system with ‘n’ components, each having reliability ‘R’

$$R_S = R1 \times R2 \times R3 \times R4 \ldots\ldots \times R_N$$

- As described earlier, R is the probability a device will NOT fail to perform its intended function during a specified time interval when operated under stated conditions.
- For systems reliability calculations, R is usually reported as a value between 0 and 1, such as 0.95

EXPONENTIAL EXAMPLE 2

What is the reliability over a 3000 hour period for an inverter system with 3 components, each with MTTF = 2,994,011 hrs?

Answer

$R(t) = e^{-n\lambda t}$ $R(t) = e^{-3(0.000000334)(3000)}$ R = 0.9969 = Probability of not failing

APPLY SERIAL RELIABILITY MODEL

EXAMPLE 1

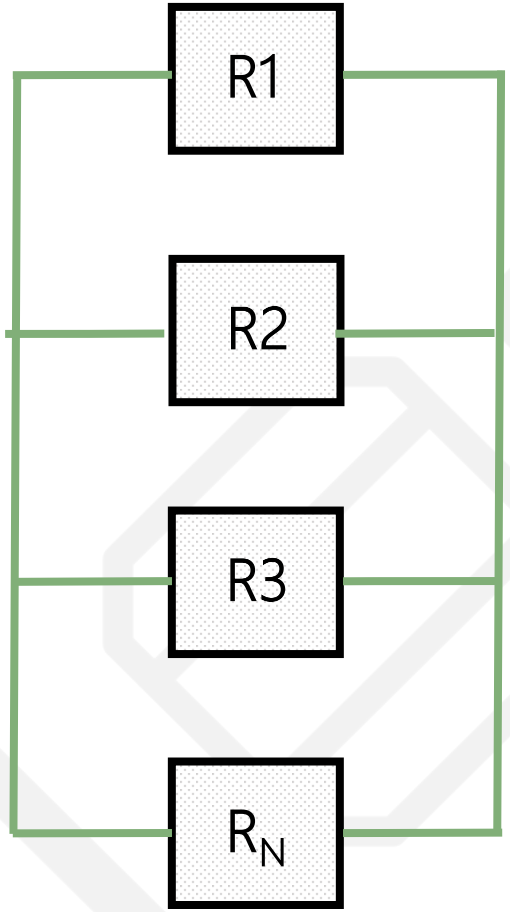
If we choose the 4 main subsystems which can lead to Failure; (A) PV panel, (B) Junction box, (C) Inverter, (D) cabling. Find the probability of failure

Component	~~MTTF~~	R(t)
PV Panel	~~50000~~	0.931
Junction box	~~100000~~	0.965
Cabling	~~100000~~	0.965
Inverter	~~25000~~	0.866

$R_s = R_{PANEL} \times R_{JB} \times R_{INV} \times R_{CAB} = 0.931 \times 0.965 \times 0.965 \times 0.866 = 0.75$, $F(t) = 0.25$

RELIABILITY OF PARALLEL SYSTEMS

(a) (b)



- System will not fail with the failure of one component.
- Redundant components will perform function of failed component.

$$U = \text{Unreliability} = 1 - R$$

$$R_S = 1 - (U_1 \times U_2 \times U_3 \ldots \times U_N)$$

EXAMPLE 1

If the same three components (A,B,C) as in the series circuit example with reliabilities of 0.92, 0.95 and 0.96 are connected in parallel, the system reliability is:

$$R_S = 1 - [(1 - R_A) \times (1 - R_B) \times (1 - R_C)]$$

$$= 1 - (0.08 \times 0.05 \times 0.04) = 0.99984$$

IMPORTANCE OF COMPONENT RELIABILITY

- Electronic suppliers normally always provide their Component MTTF levels in data sheets in order to understand likely failure level under normal application

- It is very important to define standard MTTF or FIT levels (Fails per Billion (10e9) pc hrs) for each Key component

- This is required to benchmark suppliers and ensure the basic INTRINSIC Reliability needs are satisfied

- Supplier must also show test data to show MTTF Target Levels achieved under accelerated Test Conditions *normally at 60% and 90% confidence levels*
  - Statistical Prediction made using Poisson or Chi Square distributions (can ask if you want more details)

2. Introduction to Acceleration testing

2. Introduction to Acceleration testing

Objective of High Stress Level testing beyond 'Normal Use'

Operational Stress Levels is to '**stimulate**' Defects

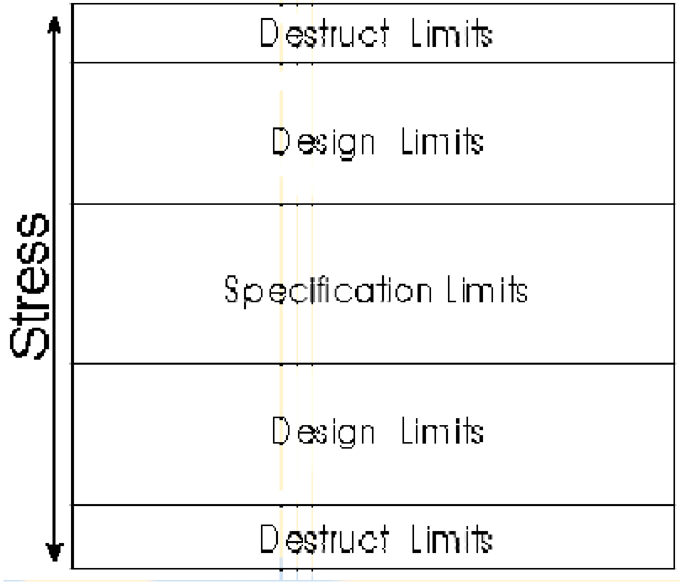
- All defects may not be resolved if it is agreed the high level of stress has caused the defect rather than weakness of Design or Component

- Testing is short and aims provides excellent Return On Investment

- Testing product in old style 40C and 25C Tests at nominal Voltage Levels with Low Humidity is to '**simulate**' field defects
  - All defects must be resolved ,but a wide range of defects will not be detected in such Low Stress Level Testing
  - Most Process Issues not detected, Component Weaknesses not detected unless very Major Issues with high defect rates
  - Testing is long in duration and poor Return On Investment

Acceleration Modelling

- Objective of Accelerated Stress Testing at Sub-Assy and Product Level is not to Damage the product, but test sufficiently to understand full range of weakness in Design and Process



- To improve Reliability we must investigate via High Stress Level Testing, then decide which issues to resolve, not to avoid Testing and miss the issues

Acceleration Modelling

ACCELERATION AT HIGH TEMPERATURES

- Chemical reaction rates typically increase with increased temperature.
- Arrhenius equation developed to represent the effects of temperature on the reaction rate.
- Equivalent to hazard rate in electronic products.

$$h(t) = e^{-E/kT}$$

E = Activation energy
K = Boltzmann's constant
T = Absolute temperature (K)

ACCELERATION AT HIGH TEMPERATURES

• Arrhenius equation can be considered to represent failure rates of components, subassemblies, systems or monitors.

• Can be re-written to represent the acceleration factor achieved at temperature.

$$AF = e^{-(\frac{E}{k})(\frac{1}{T1}-\frac{1}{T2})}$$

E = activation energy,
K = Boltzmann's constant,
T_1 = Test Temp,
T_2 = Usage Temp

• Acceleration factor (AF) is equivalent to the ratio of the failure rates.

• Experience shows that activation energy of 0.5 – 0.8 eV applies to opto/electronic systems, perhaps inverters
• Boltzmann's constant is equal to 8.617×10^{-5} eV/K.

Arrhenius Acceleration Factors

Component / Mechanism	Activation Energy
Slow trapping charge injection	1.3-1.4
Electro-Migration	0.5-1.2
Intermetallic Growth Al/Au/Ag	1
Corrosion	0.3-0.6
oxide defects	0.3
Opto-coupler LED	0.4
Discrete LED's	0.8

		Activation energy		
test temp (degC)	Usage temp (degC)	0.3	0.5	1
50	25	2.5	4.5	20.4
75	25	5.4	16.4	269
100	25	10.5	50.2	2516
125	25	18.8	133	18000
150	25	31.6	315	99000

- Many researchers select too high a level to maximise test acceleration factors and reduce sample sizes.
- Can produce erroneous data, especially when test temperatures are as high as 150°C.
- Activation energy selected should of course represent the dominant failure mechanism, but when there are potentially multiple failure mechanisms, a more conservative approach should be used.
- Average activation energies selected can range from 0.45 to 0.7 or 0.8 in some cases, hence analysis of test data will be very different.
- Experience is very key in reliability modelling – very reliant on judgement and previous experience

EXAMPLE 1

Two high temperature tests on PV bias pass diodes showed exponential characteristics with the following results:

Temp = 55°C, Sample = 200, Duration = 2450 hours, # Fails = 12
Temp = 40°C, Sample = 300, Duration = 1800 hours, # Fails = 6

What is the monthly failure rate at ambient temperature in Brasov today - (BBC weather says 25°C), assuming it experiences current of 250 hours? Clue: Find AF between two tests to find EA. Then find

Answer

$F(t) = 1-e^{-\lambda t}$; $\lambda = -\ln(1 - F(t)) / t$

$\lambda_{55} = -\ln(1 - 12/200) / 2450 = 25.26$ ppm/hour

$\lambda_{40} = -\ln(1 - 6/300) / 1800 = 11.22$ ppm/hour

$AF_{55/40} = 25.26/11.22 = 2.25 = e^{(-E/K)\ ((1/328) - (1/313))}$

$\ln(2.25) = (-E / 8.617 \times 10\text{-}5) \times (1/328 - 1/313)$; $E = 0.478$ eV

$AF_{55/25} = e^{(-0.478/K)\ ((1/328) - (1/298))}$; $= 5.48$

$\lambda_{25} = 25.26 / 5.48 = 4.60$ ppm/hour

$F(250) = 1 - e^{-\lambda t} = 1 - e^{-4.60 \times 10\text{-}6 \times 250} = 0.115\%$

Corrosion Modelling

• Corrosion is metal degradation due to chemical or electrolytic reactions in the presence of moisture, contaminants, and bias/light.
• Used for damp heat modelling
• Corrosion rate is a function of temperature (T), relative humidity (RH).

With no applied voltage:

$$AF = \left(\frac{RH_{Test}}{RH_{Use}}\right)^{n} e^{-(\frac{E}{k})(\frac{1}{T1}-\frac{1}{T2})}$$

n is dependent on the failure mechanism. Values of 2 to 4 are common. E.g. a value of 2.7 is used for busbar corrosion.

RH_{test} = Relative humidity during stress test.
R_{use} = Relative humidity during application.
E = activation energy in electron volts.
T_1 = temperature during stress test (K).
T_2 = temperature during application (K).

PEARL PV

Corrosion Modelling with Voltage/light

With applied voltage: (this can also be used for light)

$$AF = \left(\frac{V_{Test}}{V_{Use}}\right)^{N} \left(\frac{RH_{Test}}{RH_{Use}}\right)^{n} e^{-\left(\frac{E}{k}\right)\left(\frac{1}{T1}-\frac{1}{T2}\right)}$$

n is dependent on the failure mechanism. Values of 2 to 4 are common. E.g. a value of 2.7 is used for aluminum corrosion.

N is dependent on the technology/failure mechanism (2 to 4 common, 3 typical).

RH_{test} = Relative humidity during stress test.
R_{use} = Relative humidity during application.
E = activation energy in electron volts.
T_1 = temperature during stress test (K).
T_2 = temperature during application (K).

Thermal Cycling Induced Modelling

• The Coffin-Manson model was originally developed to model thermally induced metal fatigue failures. It has since been used to effectively model thermal induced stress failures occurring anywhere packaging/encapsulation

$N_f = C_o \times (\Delta T)^{-m}$

N_f = Number of Cycles to Failure
C_o = Material dependent constant
ΔT = Temperature cycle range
m = Failure mechanism dependent constant

Acceleration Factor = $(\Delta_{us}T_e / \Delta T_{stress})^{-m}$

Where ΔT_{stress} is the temperature cycle range during testing and ΔT_{use} is the temperature cycle range in the product application.

The Coffin-Manson exponent (n)

The Coffin-Manson exponent (n) is dependent on the failure mechanism and can be influenced by the encapsulation materials (glass, plastic etc), manufacturing process, module size, etc. Typical values are:

- 1 to 2 for failure mechanisms related to hard metals e.g contacts.
- 1.2 to 2.5 for mechanisms related to ductile materials.
- 3 to 10 for failure mechanisms related to brittle materials.
- 2 for determination of equivalent cycles at different conditions.
- 4 for package delamination.
- 5.6 for silicon cracking.

- If you are not sure about the appropriate exponent to use, err on the side of caution by using a low value (such as 2.0) as tis will result in a low acceleration factor.

Example – thermal cycling

PV module exposed to Thermal Cycling. Profile is Temp Cycle between -40C and +110C, 24 Cycles (each Cycle is 1 hr duration). Assume the material is 'brittle', find the acceleration factor.

Answer

Estimate the change in temperature ΔT_{use} in e.g. Malta – 20K

AF = (20/150)^-3 = 412

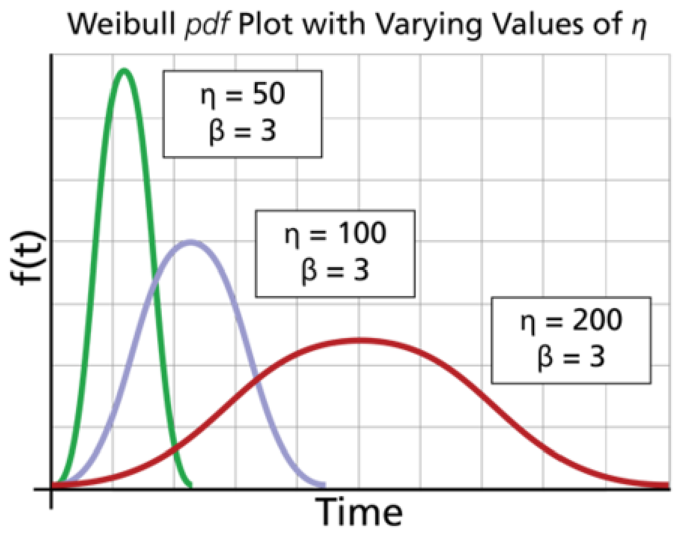
Weibull Distribution and life models

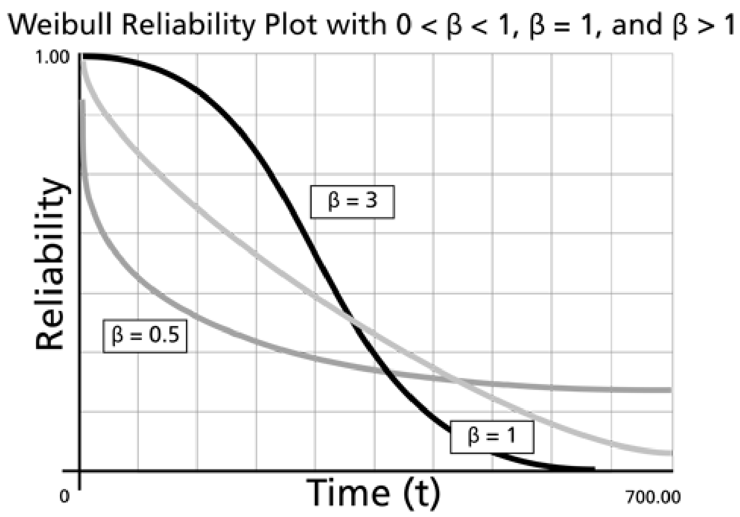
- The Weibull is usually used as a two-parameter distribution:
  - -Shape β
  - -Scale η

- η is the characteristic lifetime
- β describes the shape or slope of the distribution
  - -β< 1 Decreasing hazard rate
  - -β> 1 Increasing hazard rate
  - -β= 1 Constant hazard rate

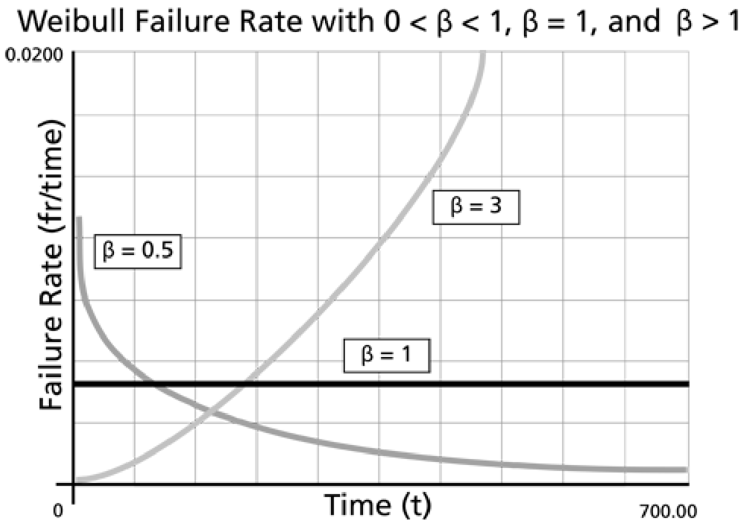
Weibull 2-p pdf

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

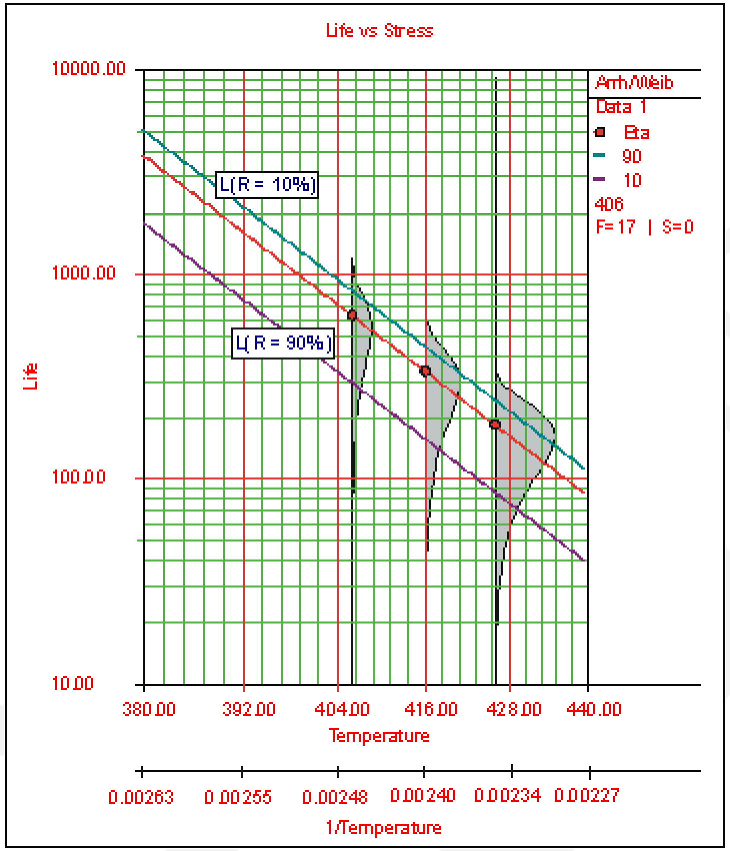




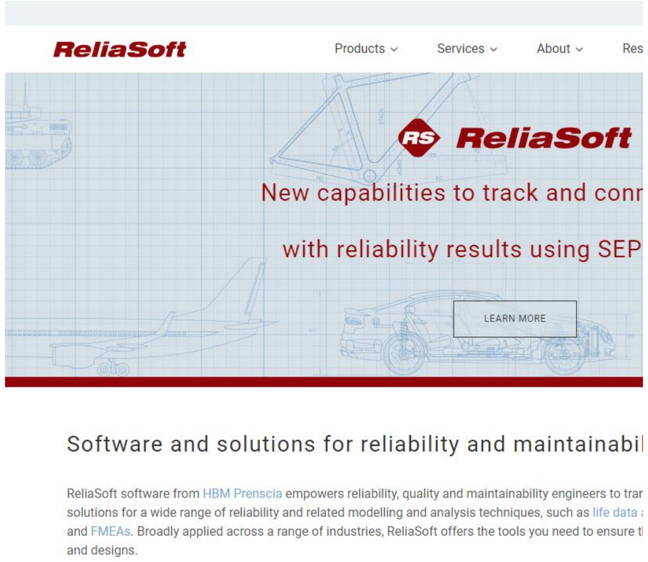
Weibull Reliability Plot with 0 < β < 1, β = 1, and β > 1
1.00
Reliability
β = 3
β = 0.5
β = 1
0
Time (t)
700.00



Weibull Failure Rate with 0 < β < 1, β = 1, and β > 1
0.0200
Failure Rate (fr/time)
β = 0.5
β = 3
β = 1
0
Time (t)
700.00



Life vs Stress
10000.00
1000.00
100.00
10.00
Life
L(R = 10%)
L(R = 90%)
Arrh/Weib
Data 1
Eta
90
10
406
F=17 | S=0
380.00
392.00
404.00
416.00
428.00
440.00
Temperature
0.00263
0.00255
0.00248
0.00240
0.00234
0.00227
1/Temperature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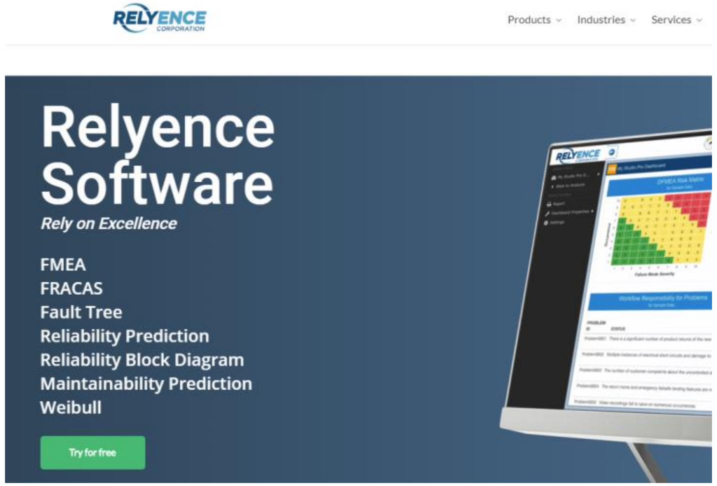
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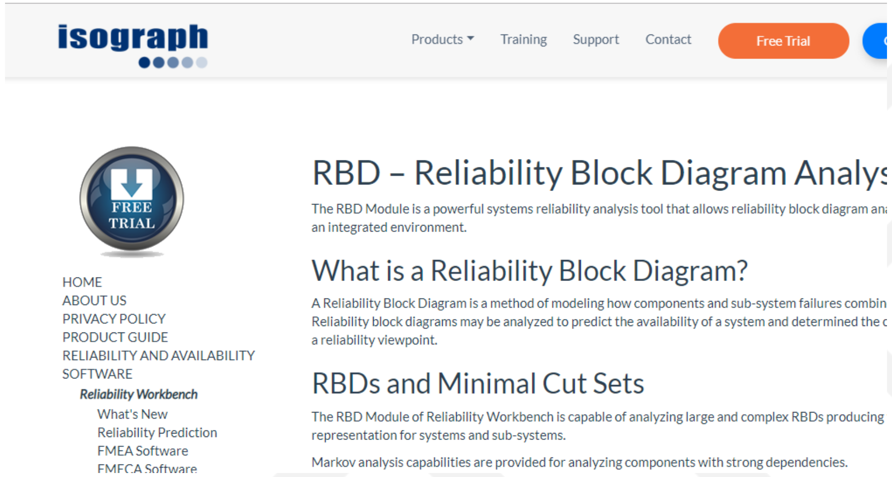
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Support
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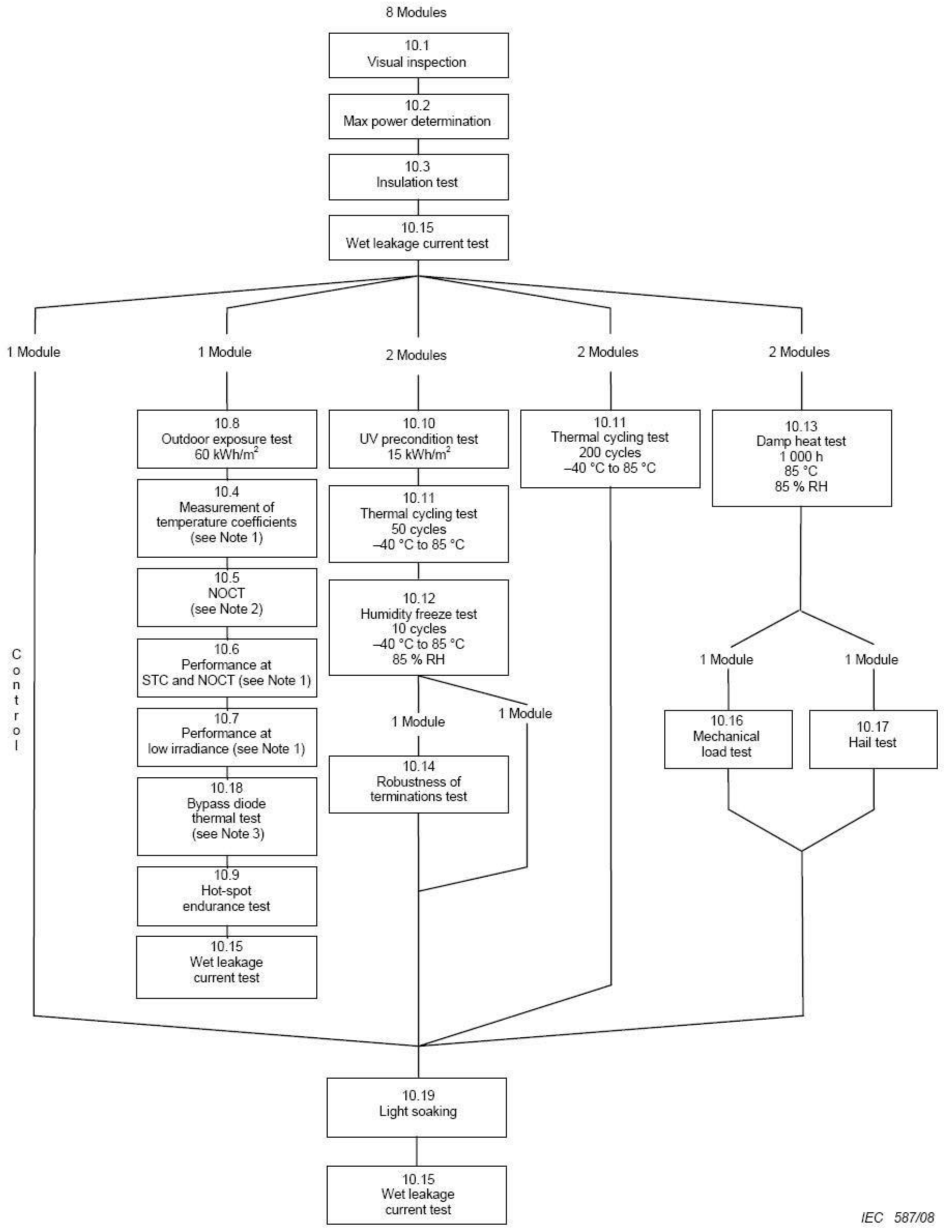
HOME
ABOUT US
PRIVACY POLICY
PRODUCT GUIDE
RELIABILITY AND AVAILABILITY SOFTWARE
Reliability Workbench
What's New
Reliability Prediction
FMEA Software
FMECA Software
RBD – Reliability Block Diagram Analys
The RBD Module is a powerful systems reliability analysis tool that allows reliability block diagram ana
an integrated environment.
What is a Reliability Block Diagram?
A Reliability Block Diagram is a method of modeling how components and sub-system failures combin
Reliability block diagrams may be analyzed to predict the availability of a system and determined the c
a reliability viewpoint.
RBDs and Minimal Cut Sets
The RBD Module of Reliability Workbench is capable of analyzing large and complex RBDs producing
representation for systems and sub-systems.
Markov analysis capabilities are provided for analyzing components with strong dependencies.

Section 3: Modern approaches to reliability in PVs

Example 1: Standard Reliability Testing



IEC 61215 Terrestrial photovoltaic (PV) modules - Design qualification and type approval

Typically used by manufacturers to guarantee module lifetime of 20+ years

Limitations

-Series of mechanism-specific tests
-Targets KNOWN failure mechanisms
- Applies at most 2 stress factors in combination
- Multiple tests requiring numerous samples = expensive and time consuming

Example 1: Reliability Testing

Field failures missed by conventional tests:

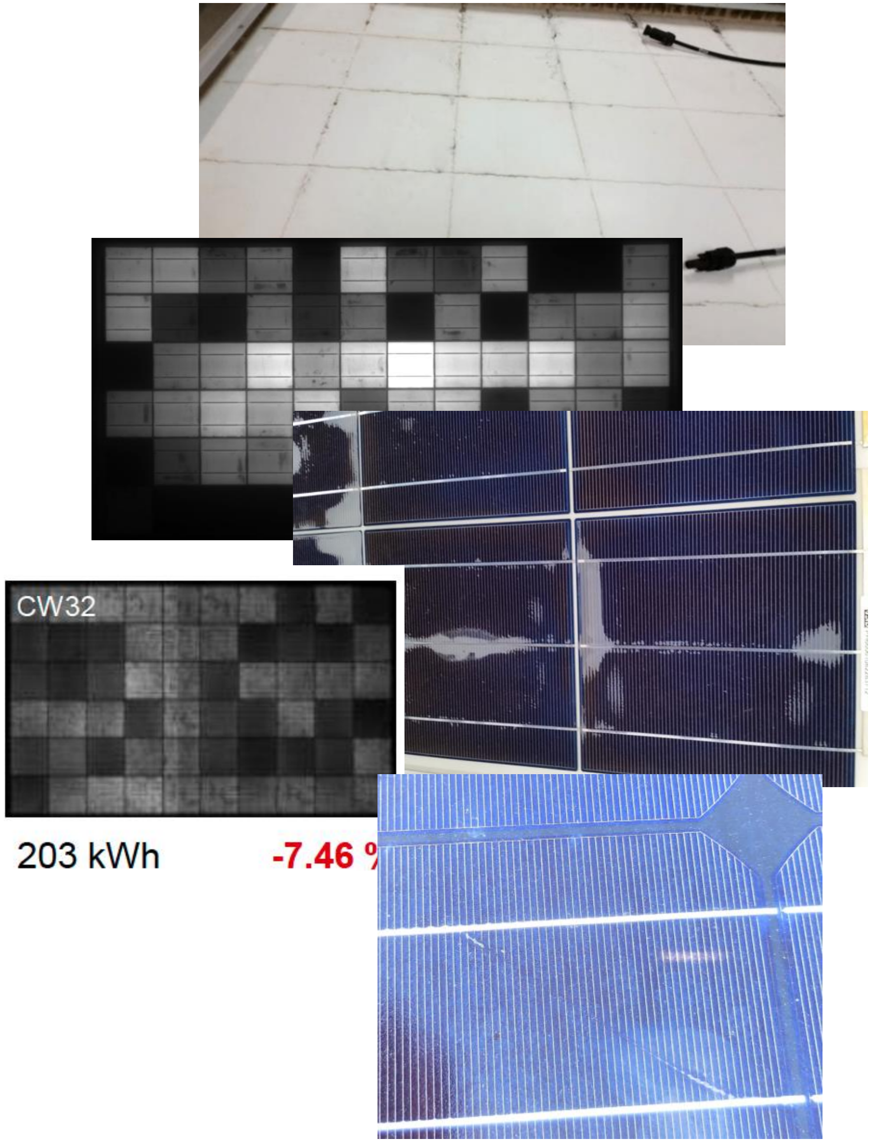
Backsheet cracking:
UV, cyclic oxidative/hydrolytic stress, CTE stress, EVA acidity

Potential-Induced Degradation (PID):
System voltage, humidity, temperature, light, soiling

Grid finger corrosion & delamination:
System voltage, humidity, temperature, light, soiling

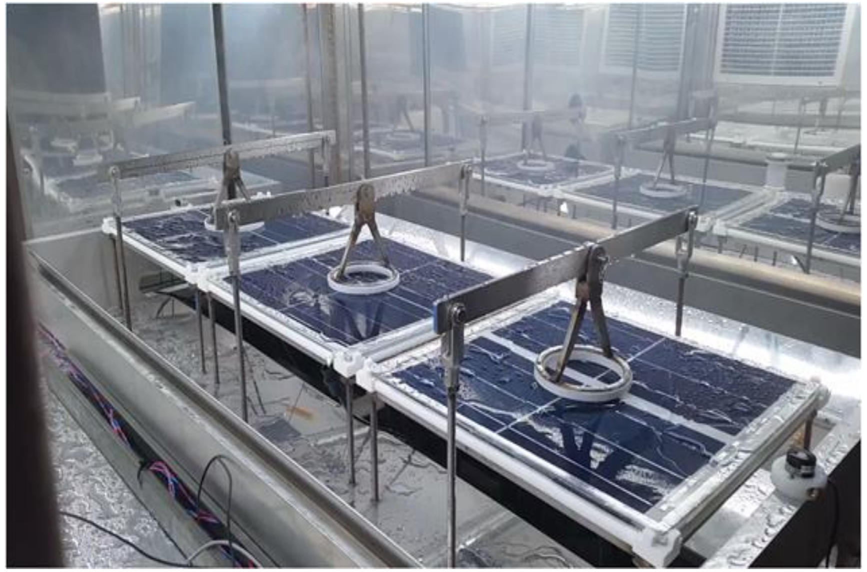
Light and elevated temperature induced degradation (LeTID):
Light, elevated temperature, current

Snail trails -> delamination:
Mechanical loading, UV, electric field, moisture, impurities



Example 1: Combined-accelerated stress testing (C-AST) developed by NREL, US

- Combine multiple stress factors of the natural environment
- Agnostic testing philosophy – not targeting specific mechanisms
- Fewer parallel tests, fewer modules = potentially cheaper and faster to certify
- Allows discovery of mechanisms not *a-priori* known in new module designs / materials
- Improved risk assessment



Modified Atlas XR-260 :

- -40°C to 90°C temperature control
- 5% to >95% relative humidity
- 2-sun Xenon-arc light exposure
- Water spray (front and back)
- Mechanical loading
- System voltage bias (±1500 V)
- Reverse Bias
- Variable load resistors
- Reflective troughs (below sample plane)

Example 2: Relying on multiple metrics for management of reliability

6 key improvement Focus Items are used which bring highest level of return in defect reduction;

1) % Design Maturity Measure based on success of Design Quality Testing
2) DFA / DFT % score based on detailed methodology and scoring
3) Early Life Reliability Test data from unique Early Life Test approach per product type
4) Process Early Life Failure escape prediction from process failure / yield data
5) ALT output / fail rate prediction
6) DFMEA summary scoring with overall scoring based on potential defect grading

- Working in a systematic manner with simultaneous focus on all 6 areas will MAXIMISE production yield, efficiency AND Reliability

Example 2: Relying on multiple metrics for management of reliability

1) Design Maturity Measure based on success of Design Quality Testing
   - *Quality Test Matrix with range of function stress tests and ELP, ALT. Failures are scored based on severity and resolution status, measures design quality*
2) DFA / DFT % score based on detailed methodology and scoring
   - *Are all failures measured by testing?*
3) Early Life Reliability Test data from unique Early Life Test approach per product type
   - *Sequential short duration stress testing required, Use mix of different stress methods to achieve high Test Strength*
4) Process Early Life Failure escape prediction from process failure / yield data
   - *Applying the appropriate model and correlating with Field Data shows how Process Yield data can be used to predict Field Fail Levels*
5) ALT output / fail rate prediction
   - *ALT cannot be standard test, must max. stress level below Design Limit, use combined range of stress methods – part of ORT*
6) DFMEA summary
   - DFMEA is important but needs to tailored for Non Standard approaches, stage of development

Acknowledgements

-Nicola Pearsall, rest of COST team (Angele, David)
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Questions?